Forecasting single-photon detector technology

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Since they cannot be generated, controlled, and measured easily, photons (i.e., light pulses) have been used to transmit information throughout recorded history. The optical communications pulses used today to transport information in the global Internet contain several hundred to a few thousand photons per information bit. The fiber-optic and free-space technology needed to generate, control, and measure the optical pulses containing such large numbers of photons is very mature, and there are numerous commercial and military optical communication systems that utilize this technology.

However, several optical communication scenarios of interest to the government and military must measure far fewer than hundreds of photons in a single pulse in order to decode a communication bit. Presently, applications requiring a single or, at most, a few photons per bit for detection are being developed and deployed. These limited photon number communication applications can be divided into the following categories: 1) stressed free-space optical communication, 2) low probability of intercept (LPI) optical communication, and 3) quantum communication.

Single-photon detectors are the key technology underlying all of these limited photon number communication applications. Single-photon detectors are devices that can reliably detect the presence of optical pulses containing only a single photon by absorbing a photon and converting its energy into a measurable electrical signal. While commercial single-photon detectors are presently available, they are expensive and have limited performance characteristics. Fortunately, single-photon detector technology is currently an area of active research, and dramatic performance improvements have been demonstrated in the laboratory. Future development and deployment of optical communication systems designed to effectively utilize a limited number of photons per bit will require the continued advancement of single-photon detector technology.

Single-photon detector technology provides detection of time-varying optical signals with performance approaching the quantum noise limit. Single-photon detectors digitize each photon detection event and its associated timing, thereby overcoming the readout noise encountered in typical photodetection schemes. This digitization provides a significant performance benefit to applications that require detecting the presence or absence of photons during many short time periods rather than measuring the total number of photons during an integration period.

For example, single-photon detectors enable very sensitive optical communication receivers for intensity-modulated signals. Additionally, most quantum key distribution protocols rely on single-photon detection. Despite these advantages, the challenges associated with single-photon detection have limited the technology's adoption and capabilities. This article summarizes the current state of single-photon detector technology, identifies optical communication scenarios that can benefit from it, and forecasts future technology advancements.

A wide range of single-photon detector technologies are likely to continue to be developed due to the different strengths of each technology and the widely varying requirements for different applications. Consequently, the technologies are likely to develop in different ways for each application, and the most appropriate scenarios to consider are application-driven ones.

Three distinct categories of optical communication can benefit from further development of single-photon detector technologies. First, stressed free-space optical communication can benefit from the improved sensitivity offered by photon-counting receivers, particularly in situations where it is challenging to couple the received optical signal into a single spatial mode. In this application, the driving requirements are the efficiency, speed, and active area of the detector. In some cases, the size, weight, and power (SWaP) of the detector system is also relevant. Second, low probability of intercept (LPI) optical communication can also benefit from photon-counting receivers' sensitivity and from their ability to collect an optical signal from a wide field of view. In this application, the driving requirements are the SWaP, the active area/array capabilities, the dark count rate, and the detection efficiency. Finally, various quantum communication applications require single-photon detectors with high efficiency, low noise, and high speed.

FIGURE 1. Single-photon detectors are already the technology of choice for the longest distance optical communication links, such as data transmission between a satellite in space and a receiving station on Earth.

The wide variety of requirements imposed by different applications and the drawbacks associated with each individual technology has lead to the development of many different types of single-photon detectors. The available technologies include detectors based on the photoelectric effect, electron-hole pair generation in a semiconductor, and excitation of an electron out of the superconducting state. Each of these technologies offer different performance advantages and drawbacks in terms of detection efficiency (i.e., optical loss), speed, noise, scalability to arrays, reliability, size, weight, and power. The evolution of each detector technology will vary depending on their application.

Stressed free-space optical communication

In stressed free-space optical communication, the extreme conditions under which communication needs to take place are the factors determining the number of photons available at the receiver. In this category, the encoded optical pulses are generated at the transmitter with a very large number of photons per pulse but, because of the nature of the link between the transmitter and the receiver, by the time the encoded optical pulse reaches the receiver, there are only a very few remaining photons available for detection.

One example of such a communication application is a satellite orbiting the moon transmitting data to a receiving station on Earth. In this application, the extreme distance of the communication link greatly reduces the number of photons per bit available at the receiver. As the link distance increases, the sensitivity of the communication receiver becomes more important and the data rate that can be supported ultimately decreases. Consequently, single-photon detectors are already the technology of choice for the longest distance (i.e., interplanetary) optical communication links (see figure 1).

Another example is communication in extreme optical environmental conditions—such as fog, smoke, or under water—where the scattering losses caused by the environment dramatically reduce the number of photons per bit available at the receiver. Depending on the system constraints and the required data rates, single-photon detectors can also be attractive for much shorter distance links. The acceptance of single-photon detectors for these applications is likely to improve as the technology and packaging mature and performance improves, particularly in terms of speed and detection efficiency as well as radiation tolerance for space applications.

The interest and acceptance of free-space optical communication systems in general is increasing, with a notable number of demonstration systems utilizing photon-counting receivers. This large and growing area should continue to support research and development of single-photon detector technologies and will thus likely play an important role in determining the evolution of single-photon detector technology.

Low probability of intercept (LPI) optical communication

In low probability of intercept (LPI) optical communication, the defining factor is the desire for communication security. In these applications, the transmitter deliberately generates encoded optical pulses that only contain a single or, at most, a few photons. For example, in LPI optical communication systems, the number of photons per transmitted bit is deliberately kept very low to minimize the probability that an adversary will be able to detect the presence of the communication link.

Single-photon detector technology provides many important attributes for enabling LPI optical communication. Specifically, this technology enables implementing a high-sensitivity receiver in a compact and scalable package, which can be designed to collect optical signals from a large number of modes. For links in which the collected optical power is limited, due to absorption, scattering, or limited power at the transmitter, the features provided by single-photon detectors can be important even for short-distance links.

In contrast to the stressed free-space optical communication application, there is a wider range of desired performance attributes for specific systems within this application. Some systems make use of the significant scattering and background-free environment available at ultraviolet wavelengths, while others may be designed to employ low-scatter, line-of-sight geometries at shortwave infrared wavelengths. In general, this application area is focused only on compact, noncryogenic technologies that can provide large active areas and/or array formats with low noise. The acceptance of single-photon detectors in this application is likely to depend on the availability of a technology that can be mass produced with high-enough performance and low-enough cost to justify widespread adoption.

Quantum communication

Quantum communication involves the transfer of quantum information between two locations. Here, the defining factor is the requirement to maintain the quantum nature of the information being transmitted. Most quantum communication systems require single-photon detectors. The most widely known and only commercially available application in this category is quantum key distribution (QKD). In QKD, ideally each optical pulse only contains a single encoded photon. Having only a single photon per pulse allows the QKD system to exploit the quantum properties of photons to provide a secure means to establish a shared secret encryption key between the transmitter and the receiver locations. (See figure 2 for a diagram of the first QKD protocol, BB84, developed in 1984.)

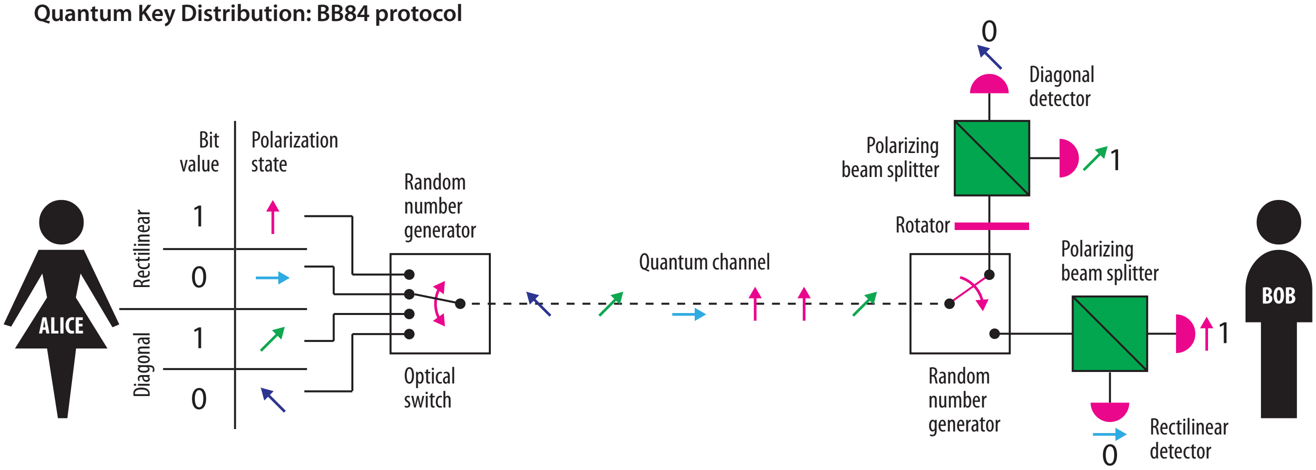
These systems have been an important area of research for over two decades. As a result, the evolution of single-photon detector technology has been driven more by the requirements of this application than by the classical (i.e., nonquantum) optical communication applications. The most important detector parameters for this application are the detection efficiency, the speed, and the noise. The performance requirements can be very challenging, particularly for some protocols or long-distance links. Single-photon detector technology development is likely to continue to steadily overcome these challenges to meet the desired performance levels.

Although the acceptance of single-photon detector technology within QKD systems is high, the growth in the adoption of these systems has been slower in recent years than some experts initially projected. More widespread deployment of these systems, beyond the initial fielded demonstrations, will likely require lower-cost systems (including the detectors) and increased security benefits relative to competing key distribution approaches.

Commercial adoption and implementation

The economic and market forces influencing single-photon detector technology are limited, particularly for optical communication. This limited influence from commercial markets can be understood given the optical communication scenarios that are likely to adopt single-photon detector technologies. Specifically, single-photon detector technology is not well suited to most commercial optical communication applications, such as fiber-optic communication systems, and

Quantum Key Distribution: BB84 protocol



Quantum transmission & detection	ALICE sends photons	↖	↗	→	↑	↑	↗	↖	↑
	ALICE's random bits	0	1	0	1	1	1	0	1
	BOB's detection events	↑	↗	↖	↑	↗	↗	↖	↖
	BOB's detected bit values	1	1	0	1	1	1	0	0
Public discussion (i.e., sifting)	BOB tells ALICE the basis choices he made	Rect	Diag	Diag	Rect	Diag	Diag	Diag	Diag
	ALICE tells BOB which bits to keep		✔		✔		✔	✔	
	ALICE and BOB's shared sifted key	–	1	–	1	–	1	0	–

FIGURE 2. This diagram shows the first quantum key distribution (QKD) protocol, BB84, developed in 1984. Although the acceptance of single-photon detector technology within QKD systems is high, the growth in the adoption of these systems has been slower in recent years than some experts initially projected.

is instead suitable for quantum communication and a subset of free-space optical communication links. There are a limited number of commercially available QKD systems that use single-photon detectors, but there are no commercially available free-space optical communication systems that employ photon-counting receivers. Consequently, most of the commercial adoption analysis will focus on the fiber-optic QKD scenario.

Several commercial companies are developing QKD systems and associated single-photon detection technologies. Both id Quantique and MagiQ Technologies have developed QKD products that use single-photon detectors. Additionally, several other companies including Toshiba Research, NTT, NEC, IBM, and Mitsubishi have developed QKD systems that are not available as commercial products but have been used in test beds or fielded technology demonstrations. In some cases, these companies have not only developed QKD systems but have also advanced single-photon detector technology or advanced the availability of packaged detector systems.

In particular, Toshiba Research and IBM have pursued new readouts and detectors, which advanced the performance of their QKD systems. Additionally, id Quantique offers a number of packaged Geiger-mode avalanche photodiode (APD) single-photon detectors that can be purchased as independent units. Despite commercial interest in these technologies, the market for QKD systems remains small and includes many research-oriented efforts to demonstrate the capabilities and to understand the vulnerabilities of these systems. Consequently, continued commercial efforts in this area will likely depend strongly on the availability of government funding to support the work and the ability of employees working on the projects to effectively advocate for internal research and development funding.

The worldwide acceptance of QKD systems that employ single-photon detectors has been slow. Although there have been some notable demonstrations of the technology in the US, Europe, Japan, and China, the technology has not been widely adopted in any region. The availability of government funding has been the primary driver in determining how the technology has been implemented as a function of time and geographic location since the cost-benefit equation governing market adoption of these systems has not changed significantly over the past few years. In the future, the system cost has the potential to change if single-photon detectors and other components for QKD systems could be integrated on a single chip with classical fiber-optic communication hardware.

As integrated photonics is more widely adopted in commercial fiber-optic communication systems, any subsequent efforts to integrate QKD functionality into those chips would be interesting to track. Additionally, the benefits provided by QKD systems would change if existing key exchange mechanisms are found to have new vulnerabilities or are subjected to new regulations. Small changes in the costs and benefits of QKD systems, including the forecasted changes in single-photon detector technology, are unlikely to generate significant market adoption of QKD systems employing single-photon detectors.

Finally, commercialization of single-photon detector technology for noncommunication applications may serve as a more powerful force influencing the development of the technology. Specifically, single-photon detectors are used in several types of instruments for measuring fluorescence from single molecules and biological samples, characterizing defects in very-large-scale integrated semiconductor circuits, and performing material analysis. Avalanche photodiode technology will benefit from governmental and commercial investments in photon-counting imaging systems that employ the same types of APDs used in optical communication systems.

The cost, complexity, and constraints imposed by current single-photon detectors can often be readily accommodated by larger-scale test equipment.

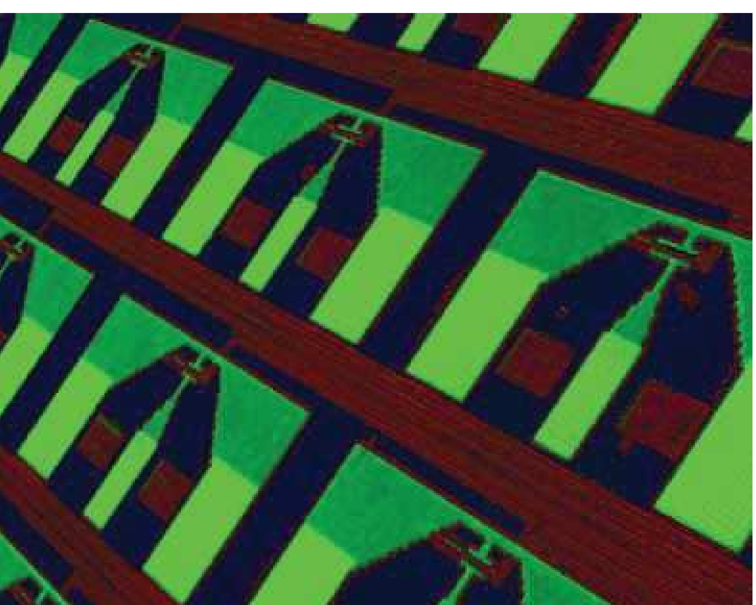


FIGURE 3. Optical microscope photographic image of an array of nanophotonic avalanche photodetectors on a silicon chip. (Courtesy of International Business Machines Corporation. Unauthorized use not permitted.)

Over time, these tools will likely be used not only by researchers in a laboratory environment but also for industrial applications in manufacturing settings and for medical applications in clinical settings. This expanded market is likely to reduce the cost and increase the robustness of technologies that are utilized. It may also drive development toward more integrated readouts and packaging, larger arrays, and improved performance. This optimization is likely to be driven by the requirements of the target application, so unless the requirements are closely matched to those of optical communication systems or the communication application has flexible requirements, other markets may have limited impact on the technology development for optical communication.

Research directions

There have been multiple decades of worldwide research on single-photon detector technologies that are suitable for optical communication. In particular, research interest in quantum optics and QKD has motivated many efforts since the 1980s to improve both the detectors and their optical and electrical interfaces. Additionally, although the advantages of photon-counting receivers for highly sensitive classical communication have also been understood for decades, efforts to demonstrate and optimize these advantages have increased substantially in just the last 10 years. Research efforts have included industry, academia, and government-funded laboratories, with most of the funding in all cases being provided by domestic or foreign governments.

Current and future research efforts to improve single-photon detector technology are likely to vary greatly in terms of the associated risks and uncertainty. Many aspects of relatively mature technologies, including photomultiplier tubes, Geiger mode APDs, and superconducting nanowire single-photon detectors are well understood and can be accurately modeled, allowing future advances to be carefully engineered with relatively low risk. In general, these low-risk research efforts are not as useful when pursued solely as proof-of-principle experiments because there is little uncertainty about their viability and impact. Instead, these research efforts are most useful when they are geared toward detectors that are well optimized for the intended application so that any trade-offs and integration difficulties can be evaluated.

Oftentimes, pursuing these advances in industry or government-funded laboratories increases the likelihood that the approach will have impact beyond an initial demonstration. These efforts can include both government-sponsored programs and, in some cases, internally allocated research funding. Government agencies or companies that are interested in fielding systems or demonstrating new capabilities are generally more likely to succeed quickly by extending the performance of relatively mature technologies as opposed to funding early research in speculative technologies. Government funding for this type of research and development is provided by defense, intelligence, and space agencies, both domestic and foreign.

In addition to low-risk detector improvements, there are also more speculative potential advancements that can be made to both mature and emerging technologies. In this case, demonstrating the viability of new ideas is important, regardless of whether this demonstration is made on a record-breaking device by a leader in the field or by an unknown researcher on a nonoptimized detector. Such breakthroughs are much harder to predict, and they are often accompanied by new engineering challenges that delay the eventual impact on optical communication systems. Although it is impossible to forecast the exact form of these single-photon detector technology breakthroughs, the speculative areas with potential for breakthroughs include photon-counting linear-mode APDs, nanoinjector sensors, quantum dot detectors, microwave kinetic inductance detectors, and superconducting tunnel junction detectors.

There is also the possibility for breakthroughs in new materials or readouts for more mature single-photon detector technologies. Speculative research areas are almost always government funded because the commercial market for such developments is not large enough to justify private investment.

Due to the scientific nature of the work, new single-photon detector technology results are generally publicly available through scientific journals and conferences; however, some foreign countries and commercial companies are less open about new results. There are numerous review articles and several books published on single-photon detectors, including a special issue of the *Journal of Modern Optics* published every two years in connection with the Single Photon Workshop. These published results generally provide a much more complete picture of worldwide technical advances than does tracking individual efforts or funding sources, many of which are small or difficult to discover and track.

Finally, it is important to distinguish between early research results and fielded detector systems. The technical challenges in maturing a new single-photon detector technology or even integrating a new approach into an existing system are considerable, particularly given the relatively small scale of most efforts in this field. Also as a result of the small scale of this field, many research advancements depend on leveraging independently developed technologies, including material growth and characterization, lithography/fabrication capabilities, readout circuits, and cooling/packaging technologies.

While this article provides a somewhat uncertain prediction of the opportunities for breakthrough performance improvements, these scientific and research advancements are only the first, vital step toward impacting actual optical communication systems.

Conclusions

Single-photon detector technology has enabled new optical communication capabilities with particular relevance for national security and defense applications. Although the optical communication systems that employ single-photon detector technology are in the early stages of adoption, it is likely that acceptance of these systems will increase, particularly with further advances in single-photon detector technology. Significant improvements in the technology are technically feasible for both relatively mature and speculative technologies, but government funding is the dominant source of investment for this work, so progress will depend strongly on the level of investment the US and foreign governments choose to make in various technologies and applications.

Future investments in speculative technologies should focus on revolutionary improvements that can impact single-photon detector technology acceptance into optical communication systems. It is not only the detector performance that will limit adoption but also the cost, maturity, reliability, complexity, size, weight, and power of the detector systems. The performance of existing detector technologies is a moving target, with continued progress likely to occur. Additionally, mature technologies provide significant advantages over emerging technologies in terms of development and past investments that can be leveraged.

In order for speculative technologies to justify significant investment, initial research into these technologies should seek to evaluate the potential for revolutionary improvements either in performance or in other metrics, such as the manufacturability, scalability, and ease of integration into systems. Existing single-photon detector technologies, particularly those operating at cryogenic temperatures, can offer fairly impressive performance, but adoption of these technologies is limited to systems that justify the cost and operational constraints associated with existing technologies. Investments in speculative technologies will most likely take many years to translate into deployable systems, but these investments are justified if they can result in revolutionary advances in system performance or widespread adoption.

In contrast, more mature single-photon detectors offer relatively well-understood opportunities to improve the performance and acceptance of systems. For many applications, increased acceptance of single-photon detectors may simply require further optimizing a technology for a specific system. Significant past investment can be leveraged to engineer and realize the required changes, while accounting for the performance and operational trade-offs. This type of optimization is relatively low risk and can be readily justified; thus, many funding opportunities for this type of work exist.

However, there are also opportunities to improve detector performance for a wide range of applications with few trade-offs or drawbacks. In particular, improved optical coupling and packaging can improve performance and may even reduce costs or improve manufacturability. An example of this is a front-illuminated fiber-coupling approach developed at the National Institute of Standards and Technology that enables very low-loss coupling to single devices [5]. Detector arrays could benefit from additional investment in low-loss microlens arrays, which might also improve back-illuminated coupling to single-photon detectors. Also, although it would require a larger investment and would have less universal applicability, improved material quality could improve detector performance without trade-offs. These types of efforts are often more difficult to justify than application-specific optimizations, but they can offer a very significant return on investment.

In summary, the future evolution of single-photon detector technology is likely to be strongly motivated by optical communication requirements as the acceptance increases for both the detectors and the optical communication systems which use them. The application scenarios and the individual technologies have many unique attributes that will likely limit the feasibility of pursuing a single, dominant technology. However, a few technologies including APDs, superconducting nanowire single-photon detectors, and transition-edge sensors do provide compelling performance advantages for specific applications.

While pursuing breakthroughs in speculative technologies is worthwhile, it is important to recognize that advancing single-photon detectors from initial demonstrations to mature components requires significant government investments. In cases where less ambitious performance improvements are sought, many opportunities remain to further optimize technologies that are already used for those applications.

About the author

The **Massachusetts Institute of Technology Lincoln Laboratory** is a federally funded research and development center that applies advanced technology to problems of national security. Research and development activities focus on long-term technology development as well as rapid system prototyping and demonstration. These efforts are aligned within its key mission areas: space control; air and missile defense technology; communication systems; cybersecurity and information sciences; intelligence, surveillance, and reconnaissance systems and technology; advanced technology; tactical systems; homeland protection; air traffic control; and engineering. The laboratory works with industry to transition new concepts and technology for system development and deployment.

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